

# **Automation Middleware and Algorithms for Robotic Underwater Sensor Networks**

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## **LONG-TERM GOALS**

The long term goals of the proposed research are: (1) To establish systems and algorithms for controlled Lagrangian particle tracking that will be used to improve the accuracy of model prediction of ocean current. (2) To achieve a mission planning system for robotic underwater sensor networks that is able to perform automatic or semi-automatic adaptation to extreme ocean conditions and platform failure, deployment, and recovery.

## **OBJECTIVES**

We plan to develop a set of automation middleware, which implement a set of novel algorithms, for robotic underwater sensor networks serving applications of ocean sampling and ocean model improvement. As contributions to fundamental research, We plan to design novel model adjustment, cooperative control, and distributed sensing algorithms that will be implemented through the automation middleware. The technical objectives include the following:

1. To investigate a new data assimilation procedure called the controlled Lagrangian particle tracking (CLPT) and its ability to provide feedback adjustments on ocean modelling systems. To design a validation and adjustment algorithm for ocean models based on CLPT.
2. To develop an automatic middleware that integrates ocean models, robot models, and vehicle control systems towards more accurate prediction of the controlled trajectories of robots in the ocean.
3. To investigate a new method called the cooperative Kalman filtering and its ability to improve data quality collected by robotic underwater sensor networks. To design a set of cooperative filtering algorithms that are able to remove noise and adjust level of details in measured ocean data to be assimilated by ocean models.
4. To design automatic mission planning algorithms for missions with multiple objectives and multiple resolutions. To design a set of efficient and effective control and navigation algorithms that utilize ocean flow to increase mobility with guaranteed sampling performance.
5. To develop a mission planning and optimization system that automatically generates control laws and mission definitions based on user input about mission goals and constraints.

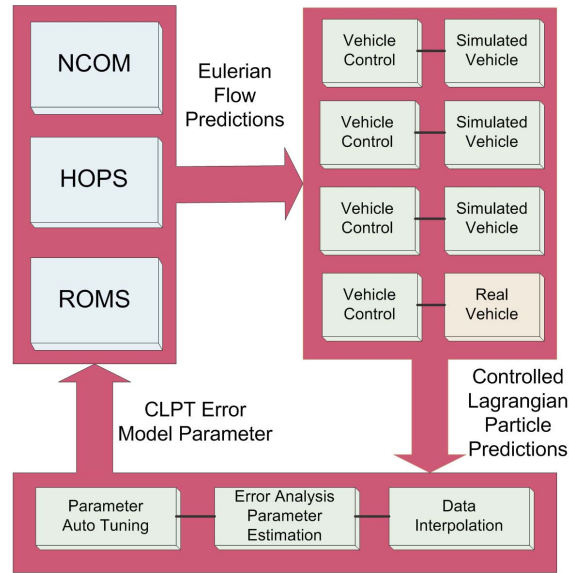
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## APPROACH

The work is performed by PI Fumin Zhang and a graduate student Justin Shapiro who entered Georgia Tech in fall 2008.

The approach and methodologies employed, corresponding to the above objectives, are as follows:

1. The PI defines the CLPT error as the difference between the predicted trajectories of the robots through simulations using ocean predictions and the actual trajectories of the robots through real experiments. This error is averaged across all robots in a network to generate the average CLPT error. The Eulerian flow predictions generated by ocean models can be improved by an automatic adjustment algorithm that minimizes the average CLPT error.
2. The PI develops a middleware system for CLPT to establish an automatic connection between the ocean modeling systems (NCOM, ROMS, HOPS) and the underwater robot control systems (GCCS or an AUV control system such as the MOOS). Figure 1 illustrates the structure of the CLPT system.



*Figure 1. Structure for the CLPT system*

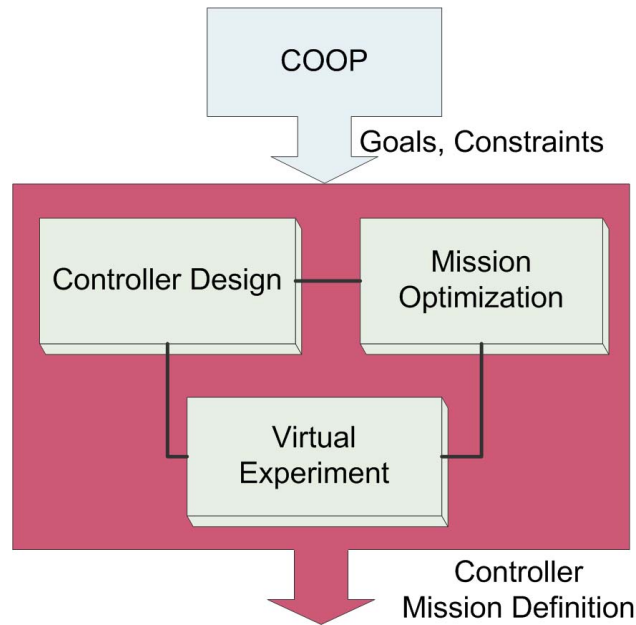
The Eulerian flow predictions generated by ocean models can be improved by an automatic adjustment algorithm that minimizes the average CLPT error. This automatic adjustment algorithm can be generalized to other ocean states such as temperature and salinity. Errors can be computed by comparing the predicted ocean states along the predicted robot trajectories with the measurements of the same ocean states along real trajectories. Similar automatic adjustment algorithms can be applied to reduce these errors.

3. We develop the cooperative Kalman filter that provides an optimal least square interpolation for ocean data collected along the trajectories of the robots. A rigorous mathematical approach is followed to justify the theoretical soundness of the method. This justifies its novelty as an extension to the original Kalman filtering algorithm (Jazwinski 1970; Stengel 1994). We apply the cooperative Kalman filter algorithm to estimate the representation error for data assimilation. Error associated with such

estimation can be minimized by optimizaing the shape of the robot cluster and the time step of the estimation.

4. We use the technique of multiple objective optimization (Sawaragi, Nakayama et al. 1985; Boyd and Vandenberghe 2002) to produce optimal mission designs that satisfy multiple objectives under the constraints for structure and adaptiveness. We address the combination of two sampling problems: feature tracking and coverage control. In both problems, the trajectories with maximum efficiency will be computed based on optimal control techniques.

5. We develop a middleware system named the automatic mission planning and optimization (AMPO) system that establishes an automatic connection between the users and the underwater robot control systems, as illustrated in Figure 2

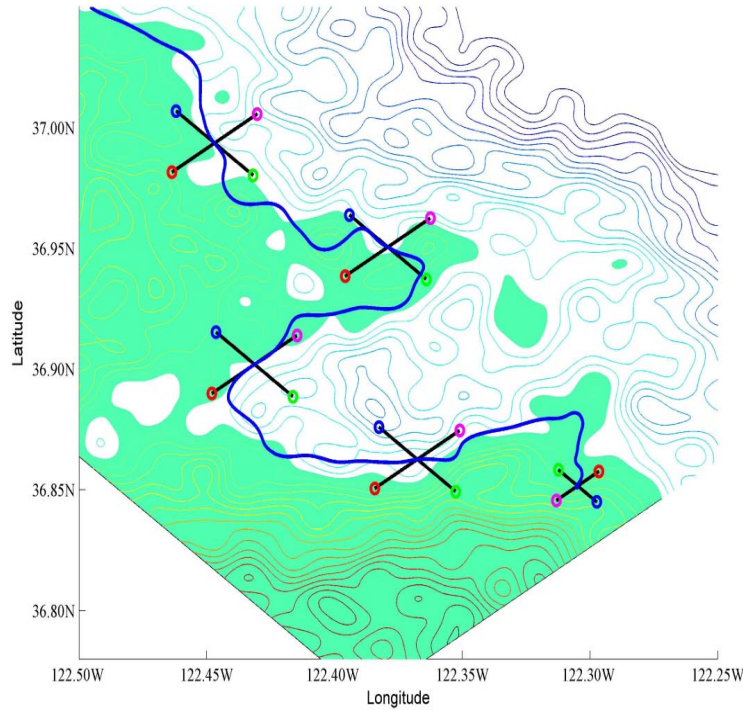


*Figure 2. System Structure for the AMPO System*

## WORK COMPLETED

Averaged CLPT errors have been computed for both ROMS and NCOM ocean models by comparing glider trajectories in the 2006 ASAP experiment in Monterey Bay, CA with recently regenerated ocean predictions. This process is named as model reanalysis. Model reanalysis reports have been generated for different versions of both the NCOM and the ROMS models. Such reports allow the ROMS and NCOM teams to test hypothesis made towards improving ocean models.

The cooperative Kalman filtering method has been developed for two dimensional ocean fields. Theoretical results show the method is provably convergent. A level curve tracking algorithm based on this method has been verified through simulation, see Figure 3.



**Figure 3. Tracking a temperature level curve using four robots. Snapshots of the robot formation are plotted along the trajectory of the center of the formation.**

Methods for evaluating performance of the middleware systems are developed under the framework of cyber-physical systems (Zhang et al 2008). Cyber-physical systems theory integrates the design of computer system and physical systems to achieve optimal overall performance. Preliminary work has been completed on predicting the performance of glider autonomy under long communication delays and asynchronicity.

## RESULTS

1. The CLPT error is a comprehensive quantity determined by four dimensional velocity fields. In the foreseeable future, no velocity observation could be available underwater over extended regions, and since gliders or other underwater robots virtually can go anywhere, CLPT error can validate models over an extended domain. As such, the CLPT error provides a unique data set for model evaluation and data assimilation.
2. The cooperative Kalman filter provides new capabilities for cooperative exploration missions with multiple underwater vehicles. It is verified for tracing smaller scale features and boundaries, which may be applied to missions such as measuring lateral mixing in the ocean.
3. Cyber-physical system theory has the potential to optimize both the performance of the mission control and the computing systems for robotic underwater sensor networks.

## IMPACT/APPLICATIONS

The infrastructure we are developing will lead to the fully automated operation of underwater robotic sensor networks that are persistent and intelligent in a constantly changing ocean environment. On top of the operation automation that results in autonomy, the data flow in and out of the autonomy is automated. This impacts not only the gathering of data, but also the assimilation of the gathered data and the improvements of ocean models.

## RELATED PROJECTS

The middleware and algorithms are connected with other important research activities around the theme of adaptive sampling using underwater robotic sensor networks.

1. Ocean modeling. The middleware design goes hand in hand with the work of the ocean modeling teams from NRL Stennis and NASA JPL. The middleware systems will provide automatic validation and adjustment methods to reduce the CLPT error to improve the accuracy of ocean flow prediction and may be applied to other state variables of the models. Algorithms in estimating the representation error will improve the accuracy of data assimilation.
2. High precision robot models. Our work will benefit from computer programs that simulate near-reality vehicles. This will further reduce the CLPT error that is not caused by ocean models, hence will improve the accuracy of CLPT.
3. Collaborative interface design. Middleware development will benefit from the continuing effort to improve MBARI COOP and other collaboration tools. On the other hand, the functionality of automatic mission and controller design will shorten the time from when a decision is made to when the decision is implemented.
4. Lateral mixing. The feature and boundary tracking algorithms developed in this project may be applied to measure tracer patches in the ocean. PI has participated in a new collaborative proposal submitted to the DRI for lateral mixing.

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